MARKET-BASED SYSTEMS FOR SOLVING SPACE EXPLORATION RESOURCE ALLOCATION PROBLEMS

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Abstract

The very nature of space exploration implies "doing that which has never been done before." As such, the resources needed to meet the objectives of such a grand endeavor, if available, are extremely scarce. Every mission since the birth of the space programme has been resource limited. To overcome these scarcity or resource issues, natural laws developed in economics can be used. Such economic systems, which are referred to as market-based systems, are based on the laws of supply and demand. Supply and demand knowledge reveals true information about users needs for resources. This information removes the need to appeal to a higher authority or multiple meetings to resolve over subscription issues.

The nature of this research programme was to apply a market-based system to a varied set of planetary exploration resource allocation problems. In the past, resource constrained problems were solved through the use of many engineers and a large number of "working" meetings. The approach was successful but was exceedingly time-consuming, labor-intensive, and very expensive. The questions addressed in this work were,

1. Could a market-based approach solve space exploration allocation problems, and
2. What were the limits of the type of problems that could be solved?

Prior to this research, only one attempt had been made to apply a market-based system to a space exploration problem. The work was performed in 1991 to solve the over subscription of mission requests for Deep Space Network (DSN) antennas. [1] The work was never approved to move from the experimental phase into an operational environment. The research described in this overview was based on the DSN attempt and then extended it to many different types of problems. This overview will discuss the application of this technique to the following four projects:

1. Development of the instrument payload for the Cassini mission to Saturn;
2. Manifest of Space Shuttle Secondary payloads;

3. Allocation of spacecraft time for RADAR observations during Earth orbital operations; and,
4. Manifest of Space Shuttles, which are destined for the International Space Station.

Results from this research prove that market-based systems can solve resource over-subscription issues faced during development and operations of planetary spacecraft missions. In addition, the application of economic principles represents a unique and innovative approach to solving spacecraft resource issues and has been incorporated into the set of management tools available to solve issues in a quicker, cheaper and faster environment.

I. Introduction

Over-subscription of resources associated with planetary exploration missions have in the past been solved by two different methods, a "committee-driven" and a "serial dictator" type of process. In a committee-driven process a group of scientist and engineers are given a problem where resources are over-subscribed. Their approach for solving the problem involved a series of meetings, followed by a series of appeals followed by more meetings.

In general, committee-driven approaches take a large number of individuals, multiple meetings to identify possible solutions, and a large number of hours to obtain a compromise solution. As in any compromise, those that get the resources are satisfied with the result, those that don't, are not. This approach also provides the incentive for individuals not to be forthright about their resource needs. Individuals realize that since the system is over-subscribed, they will always get less than they request. As such, some individuals adopt the strategy of asking for more than required in hopes that the allocation is close to their needs. This strategy aggravates an already difficult situation.

An alternate method, known as the serial dictator method (also known as a simple draft), requires an independent educated individual (or group) to collect requests from multiple users. It is then up to the dictator to determine the value of the requests based on limited information provided from the users and then to assign an allocation that returns the greatest value to the mission. This approach has the major shortcomings that the serial dictator does not have all the information that the users have or the knowledge of the compromises that can be made. The serial dictator has to determine what is "fair" and what has the greatest value to the mission with only partial data.

The question is, can another process be found that produces the same caliber of results with a smaller workforce and in a shorter amount of time? The answer to this question is yes, and a market-based system will be shown to be that process.

II. Market-based Systems

Market-based systems are systems that use the economic forces of supply and demand to obtain a user's true value for a given set of resources. To set up a market-based system, an economy must first be created. To do this, three quantities must be defined a) a currency and how it is used, b) the resources to be allocated, and c) the rules for making and keeping track of trades. [2] In this system, users express their demand for resources by making a "bid." A bid is defined as a request for a specific amount of resources in exchange for a specific amount of currency. During our research programme, the unit of currency was called "points." User where allocated points at the start of each experiment and were free to bid as few or as many as they desired to try to acquire resources. At the end of each experiment users were allocated a new budget of points.

To examine the properties of a market-based system versus the current systems, experimental economics was employed. Experimental economics uses a laboratory setting to test the performance and characteristics of individual behavior in a particular environment. An analog of an Experimental Economist's laboratory is an Aeronautical Engineer's wind tunnel. In both cases a controlled environment is used to test a predicted behavior against actual results. For a more detailed description of market-based system methodology, see Smith (1982) [3], Ledyard, et. al. (1994) [4], and Plot (1994) [5].

In the laboratory, experiments were performed which varied initial conditions to observe the resulting outcomes. In this way, experiments were set up that modeled the current system for allocating resources. Results from these experiments were compared with alternate approaches. The main components of these experiments were the:

a) Definition of what is to be allocated (i.e., the type, level, and timing of resources that are in demand by users to meet their goals),

b) Establishment of individual incentives (i.e., motivations for decisions to be made), and

c) Definition of the process by which resources are allocated to individuals (this includes all the paperwork, accounting, and information systems required to make the process "real")."[6]

An interesting challenge of the experiment design was to determine the rules for ending each experiment. An experiment was the unit of time in which resources were allocated and was known as a planning period. If a planning period ended at a specific time, all users would have the incentive to wait until the last minute to make their bids. This bidding approach keeps the bids low and rewards those users that were quick rather than promoting the highest value bids. Alternatively, the system could be designed with a random closing time. Unfortunately, this type of closing rule can produce the undesirable result of a premature closing before all users can submit bids.

For our planning periods, we used a "popcorn" model approach. That is, as long as the market was "popping" (i.e., bids were being submitted), the market stayed open. Each planning period was divided into an unspecified number of rounds. A round was the unit of time bids could be submitted. Each round had a fixed duration and closed at a specific time. Upon closing, the algorithm calculated the number of points bid for that particular round and then began a second round. When the second round closed and a point total calculated, a third round was initiated if, and only if, the point total bid for round two was 10% greater than round one. Thus, a new round n+1 would only be initiated if round n had a point total TBD% greater than round n-1. Though the percentage increase could be set at any value, for our experiments, the percent increase was set at 10%.

This stopping rule had the desired effect. As long as users were upping their bids, addition rounds would be initiated and the planning period stayed open. Once the bidding slowed, the value of the round would only represent a marginal improvement over the previous round. If the bidding provided a result that was less than 10% greater than the previous round, the planning period closed. The final result represented the best allocation of resources based on user input.

Market-based systems can be divided into two types; property-rights and an after-market system. In a property-rights system, users have currency but do not "own" any resources. This system is used to establish ownership. Once property-rights have been established a second type of market-based system, known as an after-market, is employed. In an after-market system, users trade resources they own for resources that they need. This system is nothing more than a formalized barter system. Economic models indicate that a property-right system or an after-market system (after the initial allocation of resources has been performed) may be used, but employing both yields the best results. Though we have not run the experiment, it is believed that cases can be found where the initial manual allocation of resources is done so poorly, that an after-market system alone cannot correct the deficiency.

Conclusions presented in this overview come from both experimental results and an actual application of a market-based system to a space exploration allocation problem. Experimental results were obtained by using graduate students in specially designed experiments. Student preferences were induced using monetary incentives that were controlled and represent the type of demands that may be present in the actual environment. [7] Students would be paid a greater amount if they were successfully able to acquire resources for their highest priority items instead of for their lower priority ones.

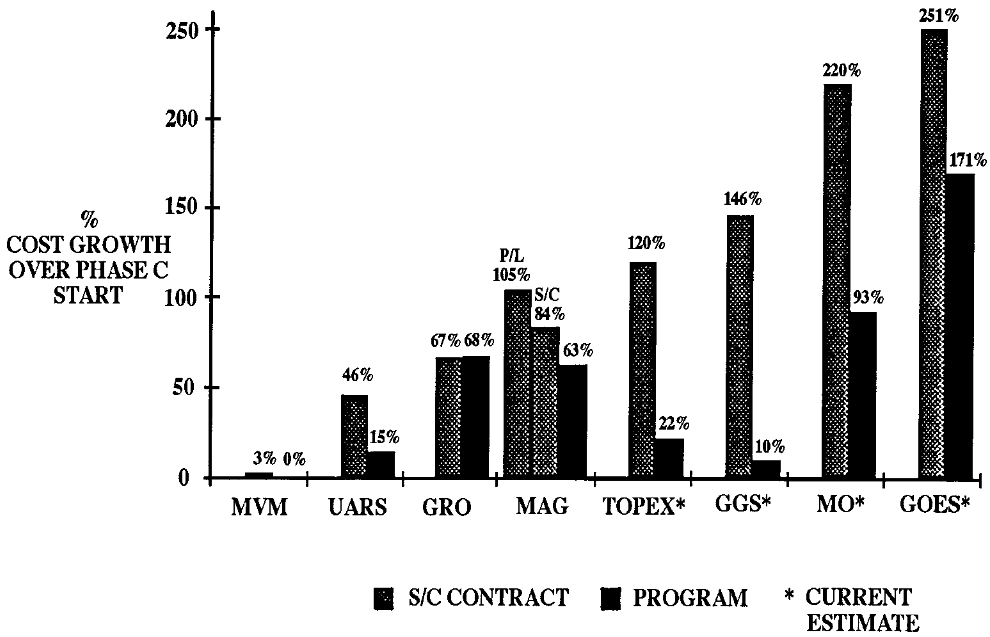
From history we see that market-based systems are not new. They have been used for thousands of years. They began when the first humans traded things they owned for things they wanted from others. However, modern day applications of market-based systems can also be seen in such varied systems as scheduling MBA job interviews at the Chicago Business School, controlling smog emissions with Southern California's RECLAIM system, and the allocation of FCC Personnel Communications Service Licenses. The challenge experienced during this research programme was convincing the science and engineering communities that a market-based system could solve THEIR allocation problems.

III. Development of Instrument Payload for Cassini

In the early 1992 the CRAF/Cassini mission faced a difficult situation. Both the Comet Rendezvous & Asteroid Flyby (CRAF) mission and Cassini, the Saturn orbiter, were being built together to save funds. Unfortunately cost growths continued which resulted in NASA having to cancel the CRAF mission. With tight budgets and the prospect of future resource growths, Cassini could have faced the same fate as CRAF. A better approach for controlling mass and cost had to be found, particularly in the area of the science payload. Cassini's science payload consisted of twelve "state-of-the-art" instruments budgeted at approximately $200 Million.

Historical data from past missions indicated that instrument cost growths were never random. That is, a decrease in an instrument's final cost over its initial estimate was usually never seen. In fact the cost growths were always positive and could be well over 200% initial estimates. If cost growth were truly random, cost decreases as well as increases should have been seen.

Figure 1. Percent mission cost growth for past space missions



MVM = Mariner Venus/Mercury (1973)
TOPEX = Topography Experiment/Poseidon (1992)
UARS = Upper Atmosphere Research Satellite (1991)
GGS = Global Geospace Science (Wind and Polar)
GRO = Compton Gamma Ray Observatory (1990)
MO = Mars Observer (1992)
MAG = Magellan (1989)
GOES = Geosynch. Operational Environ. Satellite

In figure 1, Polk (1994) shows the percent increase in Program cost from Phase C (i.e., during development) as compared to the actual cost. [8] Though it is difficult to tell the source of all of the increases (e.g., launch delays, damage during assembly, booster manufacturing problems, etc.), the data shows that costs growths are always positive. As an example of this, notice that the Magellan (MAG) RADAR payload grew by 105% during the time between its final design and the final assembly of the instrument.

In desperation, the Cassini Project decided to employ a market-based system for controlling instrument mass, power, data rate, and cost. This system was an after-market type of system since initial resources had been formally negotiated with each Science Investigator. Their negotiations are documented in their "Letter of Agreement", signed in 1992 and recorded in the Project's Policies & Requirements Document. [9]

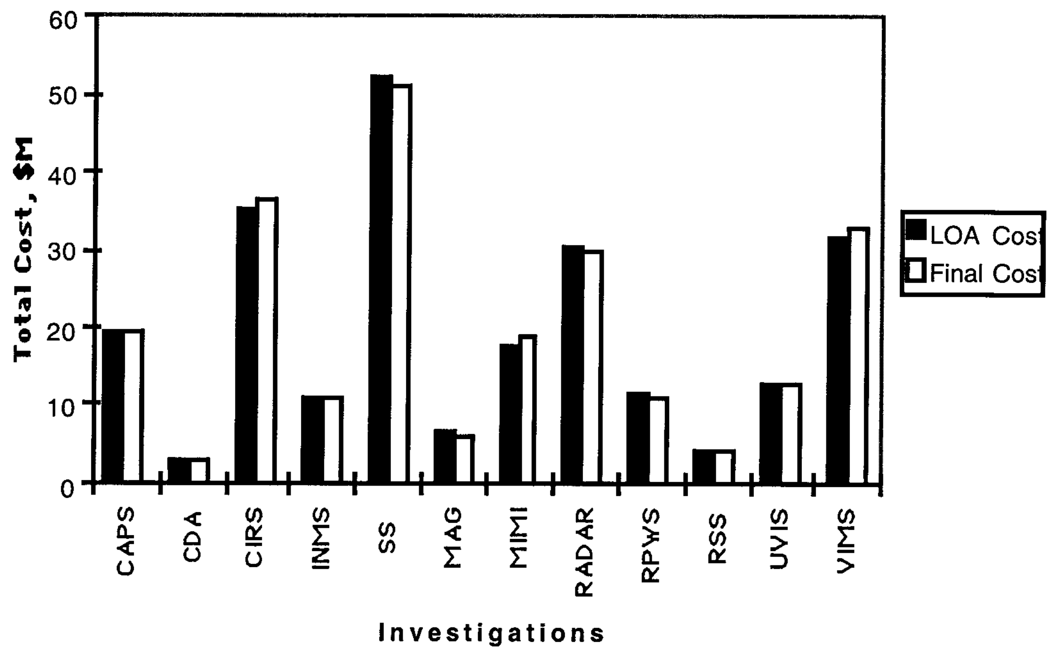
To insure that a market-based system would have a chance to succeed, the Project adopted the relatively strong position that no additional Project resources would be used to save any instrument that was having resource difficulties; and that no instrument was immune from being removed from the spacecraft. The only option available to the Instrument Development Managers experiencing development problems was to trade resources.

To facilitate trades of many interrelated resources, an organized exchange was designed and implemented. This system, known as the Cassini Resource Exchange (CRE), and allowed Instrument Development Managers to submit requests for resources in exchange for others. As an example, the Imaging Science Instrument Manager could submit a request for dollars in exchange for kilograms of mass, if the imaging instrument was running out of dollars but was coming in lighter than expected. The advantage of this computerized system was that it allowed Instrument Managers to "package" bids. That is, if an instrument needed more power in a number of modes (i.e., 1 additional watt in Mode A, 3 watt in Mode B, and 2 watt in Mode C) in exchange for $12 K in Fiscal Year 1995 (FY95) and $13 K in FY96, the system could find it if such a complement request existed. The system could also find "chains." If Instrument Manager A was trading power for mass and Instrument Manager B was trading mass for dollars, the system would find the Instrument Manager who was trading dollars for power to complete the chain, if one existed.

The Cassini Resource Exchange went on-line in 1993 and was available to any Instrument Manager until early 1995. During that time 29 successful trades were made, all but two involved dollars and mass. In retrospect, even though the CRE could evaluate trades that involved multiple instrument operational modes for power and data rate, the complex nature of these bids made it too complicated for the Instrument Managers to consider.

Once the system closed in 1995, tables were generated to compare initial and final instrument mass and costs. Figure 2 shows the twelve instruments with their initial cost estimates, as specified in their Letters of Agreements, as compared to their final costs. Though some instrument costs increased, some actually decreased. The overall cost growth for the entire science payload grew by less than 1%. [10]

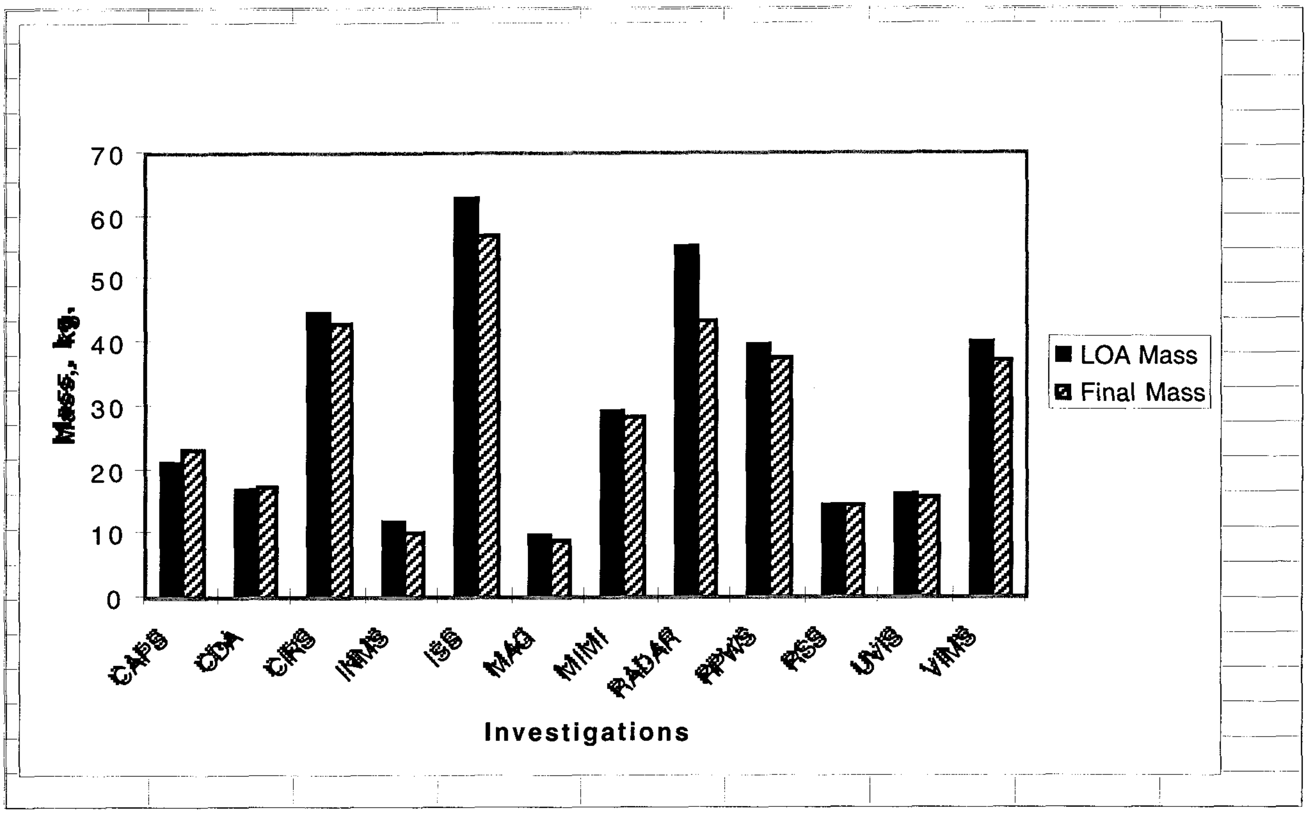
Figure 2. Cassini science instrument's cost growth.



CAPS - Cassini Plasma Spectrometer
MIMI - Magnetospheric Imaging Instrument
CDA - Cosmic Dust Analyzer
RADAR - Cassini RADAR
CIRS - Composite Infrared Spectrometer
RPWS - Radio and Plasma Wave Subsystem
INMS - Ion and Neutral Mass Spectrometer
RSS - Radio Science Subsystem
ISS - Imaging Science Subsystem
UVIS - Ultraviolet Imaging Spectrograph
MAG - Dual Technique Magnetometer
VIMS - Visual and Infrared Mapping Spectrometer

The results were even better for mass. Figure 3 shows that the overall mass growth for the science payload decreased by 7%! [11] Instrument Managers were able to return mass back to the spacecraft subsystem. The cost and mass of the science payload did not grow since there were not excessive demands for those resources. Demand (and the associated growth) was kept low since all instruments did not experience growth in the same areas. As such, Instrument Managers were able to trade those resources that were in excess for those in need.

Figure 3. Cassini science instrument's mass growth.



A surprise produced by the CRE was the ability to have a "mass auction." The electrical antennas for the Radio & Plasma Wave Subsystem (RPWS) had to be moved from the spacecraft bus to the end of the Magnetometer Boom for spacecraft stability reasons. The impact of the move was that the RPWS team was going to need either an additional 14 kg of mass plus $326 k for the thicker 1.125" diameter antennas or zero mass plus the $626 k for the new 0.75" antennas. The problem was that the Spacecraft Development Office (SDO) did not have the funds to pay for the thicker antennas that were desired by RPWS. Fortunately they did have excess mass.

The solution was to hold a mass auction. The SDO gave RPWS team 14 kg and then offered mass to the highest bidder to raise the $326 k. The auction accepted "blind" bids from any science team that needed additional mass. Teams submitted bids in the form of X kg. at $Y/kg. The bids were opened by the Project and arranged in descending order according to the highest $Y/kg. Mass was sold until the required funds were raised.

The auction produced 10 bids requesting more than 20.4 kg of mass. The average bid price was $46 k/kg. The Project sold 4.63 kg at an average price of $70.35 k/kg. [12] The result was that RPWS got the thicker antennas and the other instrument teams were able to increase their mass allocations to solve their development issues.

The CRE was not without problems. Though the system was "computerized", virtually all Instrument Managers made their requests via e-mails. It was up to the Project to enter their requests into the CRE to find successful trades. It is hoped that the growing influence of the World-Wide Web and the increased familiarity with browsers would enable future users to input into the system themselves.

Another flaw was the lack of a connection between the Development Phase and the Operational Phase of the mission. NASA does not currently allow resources to move from development to operations. When eleven of the twelve instruments were completed, the incentives to trade with the struggling instrument vanished. If, on the other hand, a user could trade operational budgets, an incentive might be created to help a struggling instrument in development in exchange for some of their funding in operations. Currently any excess development funding was used to augment an instrument's operational capabilities. Instrument teams knew that any funding not used in development would be re-assigned back to NASA.

The Cassini Resource Exchange was the first true application of a market-based system to solve a space exploration allocation problem. The success of such a system indicated that an after-market approach was a viable approach and should be considered for future space-related issues. The next question was, would a market-based property-rights type of system also be as equally useful?

IV. Manifest of Space Shuttle Secondary Payloads

Building upon what was learned from the CRE, a property-rights application for manifesting Space Shuttle secondary payloads was approved by NASA's Office of Space Utilization. The task was to determine if an electronic, market-based system could reduce the time required to manifest Space Shuttle secondary payloads while still producing the same caliber of manifest. Secondary payloads are those payloads that are stored in the middeck lockers on Space Shuttles. These payloads can be no larger than 44 cm wide by 25.4 cm high, have a maximum mass of 24.5 kg and may not require more than 130 watts on orbit. [13]

The work to address the manifest problem began in the summer of 1996 when a series of economic experiments were designed and implemented. [14] The challenge was to design a system that could perform as good as the current approach but be more efficient as the current system. In the current approach, users from the various NASA organizations submitted requests for the number of lockers and supporting resources needed to accommodate their payloads. Once submitted, the users had to wait for a second group of individuals, known as manifestors, to produce the list of payloads that would be accommodated by the upcoming shuttle flights.

Initial NASA requirements indicated that a simple application of the DSN market-based property-rights system would not suffice. NASA had a concern that the highest priority payloads may never get manifested with a market-based system. This could result if two lower priority requests, each using half of the resources (requested by the highest priority payload) and if the sum of the two lower priority payload bids was higher than the single highest priority bid. As an example, if a user bid 200 points for one locker (for what NASA considered the highest priority payload), a market-based system would always select two other payloads if their combined bid was for 201 points (e.g., 101 and 100 points).

or higher and if they both requested only half a locker. As such, the highest priority payload may never get launched.

To solve this problem, the market-based system was designed with three priority classes. User would define their payload, assign a priority class, and then specify a bid. The algorithm first manifested the shuttle with just the priority class 1 payloads. Once complete, the system would attempt to fill the remaining resources with any of the priority 2 payloads. The algorithm would end after attempting to fit any priority 3 payloads into the remaining resource envelope.

The use of priority classes addressed NASA's concern but decreased the efficiency of the system. The relatively arbitrary nature of having classes placed another variable on the problem such that it moved the solution away from an optimum. But was the solution obtained by this system better than what could have been done with only manifestors?

The metric used to evaluate one manifest as compared to another was to sum the science value of the payloads of both the simple ranking and market-based manifests. The manifest with the greater science value was deemed "better" than the one with the lower value. Prior to running the first experiment, users at NASA Headquarters assigned the science value for each payload. The actual values assigned were not as critical as the fact that different payloads had different values. If a NASA manager assigned the same value for each of their payloads, the values would indicate that the manager had no preference of which payload to manifest first. As such, the manifestors and the market-based algorithm would always select the payload with the least resource requirements since it was the easiest to manifest. A science value, assigned to payloads was only needed for experiments and would not be needed for an operational system. The values only provided preference information for the students as to which payloads to submit bids for. Students were paid according to the overall science value of their payloads that were successfully manifested. In an operational system, the incentives to bid correctly is the user's desire to produce scientifically significant results from their "best "payloads.

Science value also provided trade-off information. Trade-off information took the form of users accepting multiple lower priority payloads over their highest priority payloads. With a simple ranking approach manifestors simply started with a user's highest ranked payload and tried to accommodate it into the manifest. However, using this simple ranking approach, a manifestor would never consider using request number two and three if request one "fit" but precluded those other requests. Trade-off information might lead a planner to select a very different set of payloads.

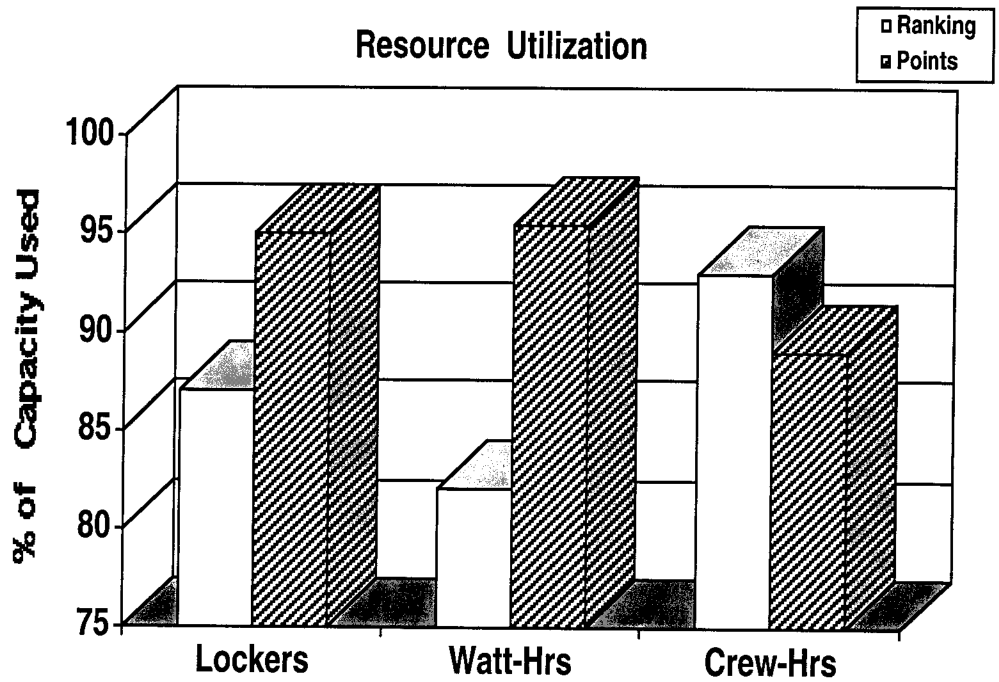
As an example, using the data in table 1, a manifestor would first incorporate MGBX-01 since it was a priority one payload. The manifestor would than try to incorporate either CGBA-04 or CPCG-07 since the Microgravity user did not specify a preference as both payloads have a priority of two. Once both number two ranked observations were either incorporated or discarded (if it did not fit into the remaining resources); the manifestor would attempt to incorporate the CPCG-08 or PCG-TES-02. The simple ranking approach has no knowledge of a user's true preferences and as such lacks trade-off information.

Table 1. An example of Microgravity's payload requests.

Payload Name	Number of Middeck Lockers	Watt-hours	Crew hours	Science Value	Priority
MGBX-01	6	237	56	100	1
CGBA-04	4	136	5.2	70	2
CPCG-07	1	128	5.8	55	2
CPCG-08	1	128	2	45	3
PCG-TES-02	3	115	0	40	3

With a market-based system students bid according to the science value since the higher the payload's science value incorporated into the manifest, the greater the students would be paid. This type of behavior, selecting the highest science value payload over a lower priority payload, is consistent with what is seen in "real life" as manifestors try to achieve the highest value manifest. In the case above, a simple ranking approach dictates that MGBX-01 be selected first since it is the only priority 1 payload. However, in our experiments the students consistently bid for CGBA-04 (science value of 70 and requiring 4 lockers), CPCG-07 (science value of 55 and requiring 1 locker) and CPCG-08 (science value of 45 and requiring 1 locker) since these payloads required the same 6 lockers as MGBX-01 but had a greater science value (i.e., 170 instead of 100). This trade-off information becomes much more important for efficiency when the number of users and the number of variables increase.

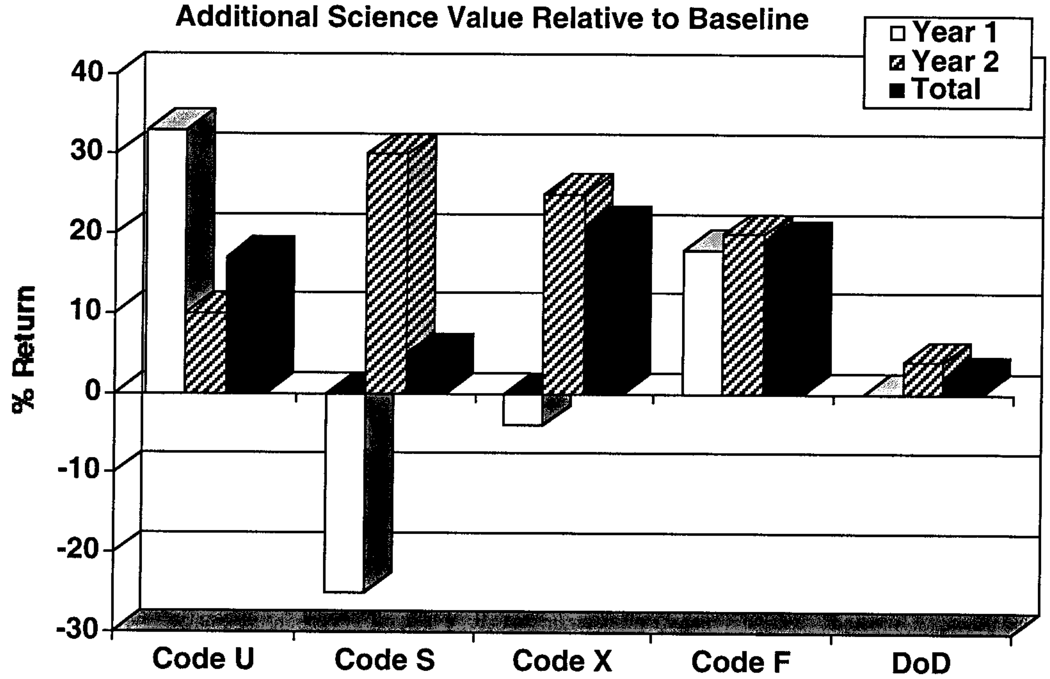
Figure 4. Comparison of resources used in a simple ranking approach (with a serial dictator) and a market-based approach.



The initial evaluation of our market-based system was inconclusive. The approach was to simply evaluate the aggregate use of resources, see figure 4. [15] All that could be stated was that a market-based system had a better utilization with middeck lockers and watt-hours, while a simple ranking approach provided a better crew-hour utilization. The reason this data was inconclusive was that nothing could be stated about which resources were more important. If crew-hours was the limiting resource then a simple ranking approach might be the better choice.

A second method for evaluating the data involved running the experiment for two planning periods. Each period involved six shuttle missions over the course of one simulated year. Thus, students first attempted to get as many of their payloads manifested on any of the six shuttles launched during year one. Any payloads not manifested or any points unspent were allowed to be carried over to the subsequent planning period. Prior to the start of the second planning,

Figure 5. Percent increase in science return for each user code using a market-based approach and their point carryovers from the first year to the second.



Carry-over	0	37	30	3	1

students were given an additional budget of points to add to any of the points from the first planning period. They were than free to bid as they saw fit during year two.

The data for this is plotted in figure 5. Notice that each user (i.e., NASA Code) on the plot has three columns. The first column is the percent return in science value of a market-based system over a simple ranking approach for the first planning period (i.e., year one). The next column is the percent return for year two. The third column shows the total return over both planning periods.

Notice that only Code S (NASA Office of Space Science) and Code X (NASA Office of Space Access and Technology) had a decrease in science value for the first planning period. This would indicate that a simple ranking approach should be better than a market-based approach for those two users. However, if we look at the number of points carried over from planning period one to two for both Code S and X, we see a different story. Both users decided to carry their points from year one to year two to insure that their large payloads get manifested. This resulted from the fact that users received points (i.e., a budget) for each planning period. By carrying points to the next year, they ensured that they had more points than the other users and thus have a greater chance of out bidding them. Both user codes decided that it would be too expensive to try to get their large payloads manifested in year one. If we look at column three for all users we see that over the two-years, all users had an overall science value that was greater when compared with a simple ranking approach.

Thus, a market-based system for manifesting Space Shuttle secondary payloads was able to produce a manifest in a shorter amount of time and with fewer people. [16] It also usually produced a higher value manifest, but this was just another benefit of the system. Our goal was never to produce a better manifest, just a comparable one done in a shorter amount of time and with fewer individuals. A market-based system also could provide the information necessary to set a commercial price for middeck lockers as compared to the approach currently used by NASA. In addition, since the system is electronically based, the system is conducive to a space program that has participants geographically located around the world.

One problem with a market-based approach was that users did not know a priori how much to bid for a locker. This resulted from two facts. The first was the lack experience on the part of the users as to how much to bid. The second was that users always bid the least amount to out-bid someone else. This resulted from the system rule that if a payload was successfully manifested in one round, the bid could not be withdrawn during subsequent rounds. It could only be bumped by a higher bid. This was done to insure that the results were monotonic and that they would converge on a solution. As an example, if a user wanted to beat a payload that was manifested for 10 points, the user would usually bid only 11 points to outbid them. Since this is a controlled experiment, we knew what the optimum bid was to efficiently manifest the most high value payloads. If the optimum bid to insure being manifested was 81 points, there could be as many as 71 rounds to get to the optimum solution! Users had no idea of how much to bid so they always bid the minimum. If a market-based property-rights system were going to be used successfully to allocate resources, giving the users knowledge of how much to bid would have to be provided.

This work was presented to NASA's Office of Space Utilization to advance the experiments into the next phase of implementation. The next phase would be to develop a system that could be used at NASA's Headquarters in parallel with their current manual manifestor system. Unfortunately, a change of key personnel at headquarters placed the entire research endeavor on hold. The explanation put forth was that since most of the middeck lockers would be filled with space station hardware, very few lockers would be available for the other users. As such there was no need to change to a market-based system in the immediate future. Their recommendation was to approach the International Space Station about the possible use of a market-based system to solve their manifest issues. After all, as the number of lockers available to users on the Space Shuttle decreased, the number of lockers available on the Space Shuttle for International Space Station payloads increased.

V. Allocation of RADAR Observations during Earth Orbital Operations

In November 1997, the LightSAR pre-project asked if we could evaluate a market-based system that could be used as a cost-effective approach for allocating time on a planned Earth-orbiting RADAR satellite. The objective of this mission was to use new technologies to develop a Lightweight Synthetic Aperture RADAR (LightSAR) spacecraft that could be used both by the scientific community and commercial users.

Past RADAR missions all had the same type of challenge, namely an excessive demand for RADAR time to observe the Earth. That is demand by multiple users far exceeded the available amount of spacecraft time for collecting data. For these past missions, users would submit requests to select a RADAR instrument configuration (i.e., Dual Polarimetry, Interferometry, ScanSAR, Hi-Res Strip, or Spotlight), the time for target illumination, and the coordinates of the target. These requests would be submitted to mission planners to integrate into a single timeline of events. The mission planner's goal was to select only the highest priority requests, be fair to all users, and efficiently used the limited spacecraft resources.

Once the mission planners had produced a timeline, it would be presented to the user community. As is always the case, those users that had their RADAR "data takes" incorporated into the timeline were satisfied with the timeline. Those users that lost out were unhappy and appealed the decision. Appeals were always made since there was "nothing to lose" and everything to gain. Unfortunately there was something to lose. Individuals that appealed to get their request incorporated into the timeline invested their time and effort as well as those of the governing body that was given the responsibility of adjudicating conflicts. Once the appeal was presented, if it was lost the user had nothing to show for their effort. This type of loss is commonly referred to as a "Dead Weight Loss." To compound the problem, users typically make multiple appeals until they were successful or the time for making changes to the timeline was past. The question was, could a market-based property-rights system produce the same caliber of timeline with fewer people, in less time, and in a distributed manner? In addition, a better mechanism had to be found which would allow users to bid in a more efficient and natural manner.

The student experiments designed for LightSAR began with the system design for the Space Shuttle manifest problem. It had been shown that the shuttle system, without the priority classes, was well suited for this class of problem and was able to provide trade-off information that made the system very efficient.

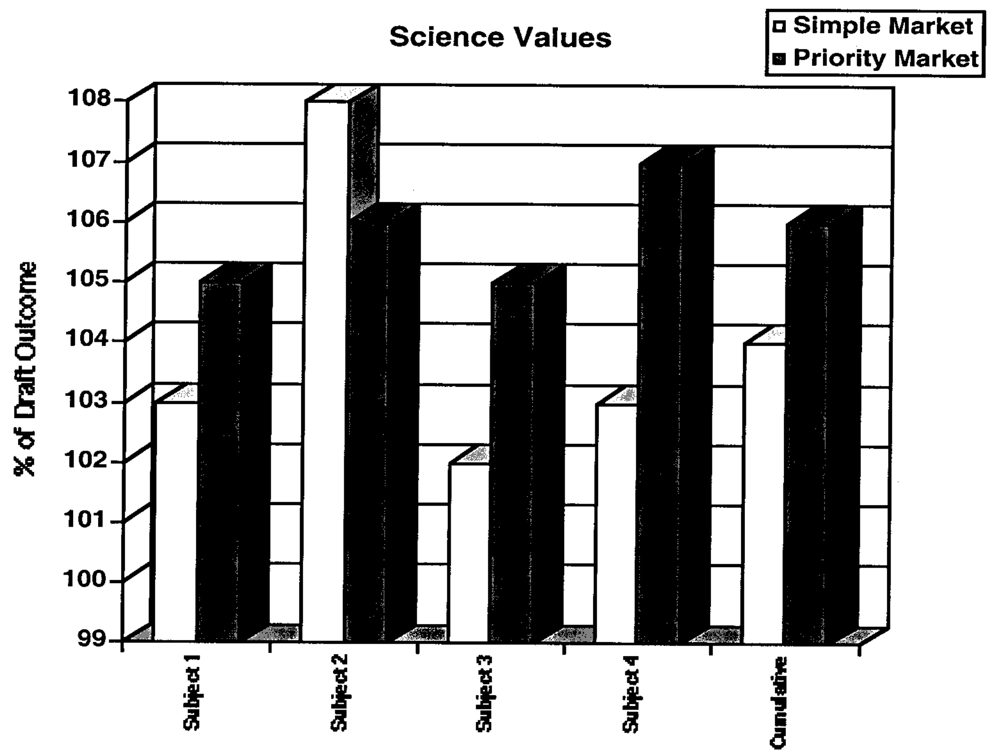
With our LightSAR experiments, the problem of a more natural way to bid and how much to bid was addressed. As we saw with the shuttle experiments, users did not know a priori how much to bid for their requests. In addition, since accepted bids could not be retracted, users had an incentive not to overbid and submitted the lowest winning bid they could to obtain the desired resources. As stated previously, this approach produced numerous small bids and an excessive number of rounds.

To decrease the number of rounds required to reach a result, a market-based system with a Vickrey auction was used. [17] In a Vickrey-type of auction, the "winning" bid pays the runner-up price. Thus if user A bids 50 points and user B bids 75 points for the same resources, user B would win the resources but would only be debited 50 points from their account.

Vickrey auctions provide the incentive for users to be forthright about their requests. This can be seen in the following example; if user C wanted a particular set of resources but tried to under-bid for them (i.e., tried to acquire the resources for a small number of points), other user could bid for those same resources with an extremely high bid. Using a Vickrey auction, the high bidder would get the resources for the price set by the lower bid. Thus the only successful way to bid in a Vickrey auction is to bid the largest amount of points that a user would be willing to pay the first time. If out-bid by a second user, the only choice left to the user who lost the resources would be to a) consider increasing their bid, b) bid for a different set of resources, or c) carry the points forward to another planning period.

Figure 6 shows experimental results produced by a simple market-based system versus a market-based system with a Vickrey auction. The figure shows that both systems out performed a serial draft approach. In addition, a market-based system with a Vickrey auction approach out performed a simple market-based system by 2%. [18] Thus, a Vickrey auction not only out-performed a simple market-based system, but also arrives at a solution faster.

Figure 6. Percent value increase of a simple market-based system and a market-based system with a Vickrey auction over a serial draft.



To help users determine the correct amount of points to bid, priority levels were designed into our experiments. By defining priority levels (different concept then shuttle priority classes), users only had to specify the priority level of the request rather than the point total of each bid. A priority level has a number of points associated it. As such, a user just specified the data-takes priority and the system would determine the bid price. The priority level was established experimentally, for if set wrong the desired outcome would not be observed. As an example of this, if experimental data indicated that a bid of 81 was the optimum bid and the priority levels were set at:

Priority Level 5 = 0.1 point,
Priority Level 4 = 0.2 points,
Priority Level 3 = 0.3 points,

Priority Level 2 = 0.4 points,

Priority Level 1 = 0.5 points, and

Priority Level 0 = user specified bid.

then multiple rounds would still be needed to get the point total to the optimum bid of 81. Thus, having priority levels with point totals too close would not sufficiently reduce the number of rounds.

Conversely, if priority levels were set with point totals too far apart, the system would have too few rounds. As an example, if priority levels were set at:

Priority Level 5 = 0.1 point,

Priority Level 4 = 1 points,

Priority Level 3 = 10 points,

Priority Level 2 = 100 points,

Priority Level 1 = 1000 points, and

Priority Level 0 = user specified bid.

then there would not be enough points in a student's budget to select data takes with a priority level of 2 since students were only allocated 150 points per planning period.

We found experimentally that an approximate doubling of points per priority level produced satisfactory results. That is:

Priority Level 5 = 0.1 point,

Priority Level 4 = 0.5 points,

Priority Level 3 = 1 points,

Priority Level 2 = 2 points,

Priority Level 1 = 5 points, and

Priority Level 0 = user specified bid.

Once the priority levels were set, users just decided which type of data-take they wanted and the priority of the request. In addition, the bid was dependent on the amount of resources requested. As such, when a priority level was selected, the point bid total was calculated by multiplying the points associated with the priority by the amount of resources requested. Thus, a data-take requiring twice the duration of a particular request would calculate a bid that was twice the number of points. This provided the incentive for users to only request the resources that they needed for their data-take requests, and nothing more. The more resources requested, the more the request would cost.

Thus a market-based property-rights system with a Vickrey-type of auction had the benefit of producing the same caliber of timeline in a shorter amount of time and with fewer people. It also produced results in a fewer number of rounds than a market-based system where bid prices had to be submitted by the users. In addition, the bidding was more natural since users only had to select the priority of the request rather than trying to determine the bid price. Users in the space exploration community are always being requested to prioritize requests. As such, using this approach, some of the fear of using a market-based system was alleviated.

The major draw back of the LightSAR system was the user unfamiliarity with market-based systems. Users were able to increase their comfort with the system after participating in a few planning periods, but the result is very surprising. In the United States individuals live in a market-based system known as capitalism. Individuals make choices to exchange currency for a resources every day. However, applied to a space exploration problem that is usually solved with a committee process or by a serial dictator approach, individuals seem to lose all their expertise in such market-based systems. The only method for removing this issue appears to be by experience alone.

The LightSAR Project did endorse the market-based approach but had a much bigger problem to address. Since the mission was half science and half commercial, the Project had to find a commercial sponsor to fund the other half of the mission. Only than would NASA ask Congress to fund it. By the fall of 1998, a commercial sponsor still had not been found. As such, funding for the mission was not included in NASA's budget.

VI. Manifest of Space Shuttles for the International Space Station

The current application still pending experimental trials involved manifesting payloads for the International Space Station. The strength of our Space Shuttle results gave us the confidence to approach this multi-billion dollar endeavor. The difficulty for this market-based property-rights system design was compounded by the fact that payloads had to fit into the resource envelope provided by the International Space Station AND the Space Shuttle. This was driven by the fact that only those payloads that fit in Space Shuttle Middeck Lockers or in the Multi-Purpose Logistic Modules (MPLM) could be manifested for the station.

Figure 7. Space Shuttle and International Space Station resource envelope.

Shuttle Missions

Shuttle Missions: 1 Flights

Flight Name		Up Mass (kg)	Middeck Locker MDL (lockers)	Multi-Purpose Logistic Module MPLM (lockers)	Middeck Power MDP (watts)
7A.1	Capacity:	2267	4	2	0
	Reserves:	226	4	2	0

Priority Class Restrictions

There are no restrictions

ISS Resources

	Middeck Locker Equivalent MDLE (lockers)	Energy (kW*hr)	Crew Time (hr)
Capacity:	50	29648	373
Reserves:	0	0	37

Close

In figure 7 we see the basic structure of the International Space Station problem. In this particular case only one Space Shuttle, Flight 7A.1, is scheduled to rendezvous with the station. The shuttle has a specific payload lift capability (i.e., 2267 kg. with 226 kg. in reserve), has the ability to store payloads in 4 lockers with another 4 in reserve, or in 2 MPLMs with 2 in reserve. In addition the station can provide some electrical power for the payloads. Notice that the International Space Station has its own set of resources (i.e., Middeck Locker Equivalents, energy, and crew time).

Like past allocation problems, the current system involved a large number of manifestors and a large number of meetings all designed to efficiently use the shuttle and station resources while being fair to all users. Another complexity of the International Space Station manifest problem is that there are two different sets of manifestors, those for the shuttle and those for the station. Thus, it is possible that shuttle manifestors might manifest a payload on to a shuttle that may not have the available station resources to operate the payload.

Figure 8. Results of manifesting Shuttle 7A.1 and the International Space Station.

Shuttle Manifests Round 1

Shuttle Missions: 1 Flights

ISS On-Orbit Payloads

Payload	User	Transportation				On-Orbit (ISS)		
		Up Mass (kg)	Middeck Locker MDL (lockers)	Multi-Purpose Logistic Module MPLM (lockers)	Middeck Power MDP (watts)	Middeck Locker Equivalent MDLE (lockers)	Energy (kW*hr)	Crew Time (hr)
BBND	HLS	0	0	0	0	3.12	151.9	1.87
Interactions	HLS	0	0	0	0	0	0.06	0.43
MAMS	MG	0	0	0	0	2	25	0.25
SAMS	MG	0	0	0	0	2.35	149.75	0
PCS	MG	0	0	0	0	4	182.16	2.25
BSTC	MG	0	0	0	0	0	0	0
Resources Left		0	0	0	0	38.53	29139.13	368.2
Capacity		0	0	0	0	50	29648	373

Shuttle 7A.1

Payload	User	Transportation				On-Orbit (ISS)		
		Up Mass (kg)	Middeck Locker MDL (lockers)	Multi-Purpose Logistic Module MPLM (lockers)	Middeck Power MDP (watts)	Middeck Locker Equivalent MDLE (lockers)	Energy (kW*hr)	Crew Time (hr)
PuFF	HLS	20.3	1.11	0	0	1.11	3.45	1.67
H-Reflex	HLS	16.9	0.33	0	0	0.33	0.25	1
Renal-Stone	HLS	9.05	0.95	0	0	0.95	0	2.05
EarthKAM	Code M	0.2	0.04	0	0	0.04	0.5	2
APCF	Code M	26.8	1	0	0	1	84.07	0
BCSS-1	MG	31	0	0	0	0	0	0
BCSS-4	MG	31	0	0	0	0	0	0
ZCG-FU	SPD	54.4	0	2	0	2	0.7	0.02
Resources Left		2077.35	0.57	0	0	33.1	29050.16	361.46
Capacity		2267	4	2	0	50	29648	373

Close

The work for this system design began in the spring of 2000. A prototype system was requested to be in place by the fall of 2000. Our approach was to use the Space Shuttle system with the fewest number of modifications. This was done to minimize costs since the International Space Station program had not allocated any funds to develop this planning tool. We believed that the strength of the prototype would convince them to fund the effort.

Results from this prototype market-based tool can be seen in figure 8. The top portion of the display indicates what payloads are currently at the station. Notice that the transportation costs for those payloads are all zero. The resources utilized by these payloads are first removed from the available station resources. The shuttle 7A.1 payloads, once docked with the station subtract their resource requirements from the remaining station resources. The last two lines of the figure shows the remaining resources left on Shuttle 7A.1 (as compared to its capacity) and the remaining station resources (as compared to its capacity). Notice that the shuttle had only 0.57 of a Middeck Locker left and no MPLMs, while the station still has plenty of resources availalbe.

With a prototype system in place, the research effort was on hold pending the release of funds to develop a system that could be used by station manifestors. The one shown above was too simple to use in actuality. By the summer of 2001 funding for the International Space Station had still not been approved. Though managers believe in the system and its ability to solve their type of problem, work has been placed on hold until funding is released. More pressing International Space Station issues have superceded the issue of manifesting station payloads.

VII. Summary & Conclusion

This body of research involved the relatively new science of experimental economics and combined economists, engineers, and scientists to develop a new approach for solving space exploration allocation problems. In this endeavor, the economist contributed their knowledge of allocating scarce resources and their expertise in applying economic tools. The engineers contributed their knowledge of current techniques and approaches for solving the problems. Finally, the science community had the pivotal role of evaluating the results of the experiments. They also participated as willing subjects to validate the proof of concept for both the software design and the utility of the displays. Both a market-based property-rights and after-market system were applied to solving a wide class of space exploration allocation problems. The research was performed in a laboratory setting to be able to vary initial conditions and to produce scientifically valid results. The combination of these disciplines, working together, was able to develop a systematic approach that to date has been beyond the grasp of any of the fields working alone.

The Cassini Resource Exchange could have been considered a fluke, but the success of market-based systems to a wide spectrum of allocation problems leads us to believe that the system was indeed capable of solving these classes of problems. In addition, our research was able to solve both initial allocation problems associated with an after-market type of system and the multi-dimensional problems associated with the bartering of resources. The CRE still represents the only successful application of these tools to a space exploration allocation problem. As previously stated, the tool was also successfully transferred from Cassini to the Air Quality Management District of Southern California's RECLAIM system. Roots of this system can be seen in the Kyoto Protocol for curbing the ever-increasing amount of greenhouse gas emissions.

With the Space Shuttle property-rights system, we successfully applied the techniques to solving shuttle manifest problems. This proved that a market-based system could solve these classes of problems even when restricted with the need for priority classes. The system was easy to use, produced superior results, required a smaller workforce, and was globally distributed. Its main attribute was that it put the individuals with the information in control of the system, namely the users themselves.

Finally we were able to remove the main technical problems of a market-based system. These problems involved finding an improved way to bid and a mechanism for reducing the number of rounds required to reach a solution. A Vickrey-type of auction coupled with using priority levels made a market-based property-rights system natural to use, increased the efficiency of the system, and increased the system's ability to find a locally optimized solution. The only remaining question is why is there such resistance to employing market-based systems to more space allocation problems?

The answer to this question appears to do more with the constituency that would support such a system than the approach itself. If we look at the user population, individuals that successfully produce above average results through the force of their demands, presentation skills, and appeals to management will never agree to change to another system. They already succeed with the current system and as such have no incentives to switch to a new system. Those individuals that consistently have below average results also are resistant to change. They have no guarantees that they will perform better with a new system but have to pay the penalty of learning a new one. Thus, from a user point of view, there are no reasons to change to a market-based system.

The only reason to attempt to use such a system comes from Project Management. This only occurs if the situation is desperate enough and the risk of mission failure so great that attempting a new innovative system appears as a reasonable risk. This is the only rationale that can explain the fact that Cassini used a market-based system for developing their science instruments but then would not even entertain the use of a market-based system for developing science timelines. All that can be said is that once in operations, there is no fear of mission cancellation. Since most observations planned in a science timeline will return a high science value, there is no incentive to aggravate the science community to increase the efficiency of their science planning process. After all, the science community will always state that they can do a much better job "working together" then in isolation bidding on the internet. Past historical data and experimental results shows us that this is not the case.

One limitation of market-based systems is that the resources being trading between users must be independent. The CRE involved 12 independent science instruments. As such, if the Visual & Infrared Mapping Spectrometer did a poor job trading, it would not effect the other investigations. However, in a dependent system, like designing a spacecraft, we see a different story. If the Attitude & Articulation Control Subsystem did a poor job trading and thus performed poorly, it wouldn't matter how good the Command & Data Handling Subsystem did, the overall spacecraft would not be able to meet the objectives of the mission.

Other factors that limit the utility of a market-based system are the number of users, the extent of the over-subscription of the resources, and the existence of known solutions. In the case of the number of users, the system gradually breaks down as the number of users approaches two. In the limiting case of two users, if one user wants to trade but the other does not, no trading occurs. A small number of users is referred to as a "thin" market and economic principles loose their meaning. A market to be viable must have enough individuals to obtain enough information about user demands. In our experiments, five users were a minimum in order to obtain satisfactory results. On the other hand, our limited experiments did not reveal any upper limit to the number of users the system could handle.

The extent to which the resources were over-subscribed is another factor. Market-based systems improve as the number of resources and the amount of demand increases. This results from the fact that many different combinations of demand exist, any of which may be used to optimize the system. Finally, even in an exceedingly over-subscribed system a known solution mitigates the need for a market-based approach. As an example, if multiple users would like to perform a RADAR observation over Java, all users would have to postpone their request if it was critical to the Project to image Mount Kelud in East Java prior to its eruption. In this case a solution already exists to which user will obtain the time to observe during the Java observing session. Thus, market-based systems are only needed when no prior solution pertaining to the allocation exists.

This research programme has been applied to Cassini instrument development, Space Shuttle secondary payload manifests, LightSAR mission planning, Mars 2001 Lander surface operations, Cassini science planning, and manifesting of International Space Station payloads. Only the Cassini instrument development effort was allowed to move from the experimental phase to an operational one. The cancellation of LightSAR and the Mars 2001 Lander missions by NASA did not help our cause. In addition, the large cost overruns in the International Space Station delegates our small research programme to the sidelines until the much large station issues can be solved. Cassini has also tentatively agreed to consider using an after-market approach once their initial allocation of resource for their 4-year science tour is fully planned. Even the Deep Space Network is considering re-examining a market-based property-rights system for allocating time on their experimental Deep Space Station #13.

However, the author believes that only when three successful applications (not experiments) have been achieved covering three different types of problems (e.g., instrument development, science planning, payload manifests, etc.) will market-based systems develop enough credibility to be accepted by the space exploration community.

VIII. Acknowledgements

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